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CORROSION OF ELECTRONIC COMPONENTS

by

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SUMMARY

The Materials Lab~~oratory~~ Electronic Failure Analysis Group supports ~~U.S. Air Force~~ USAF electronic systems in the areas of materials and manufacturing processes. It has been established that a large majority of electronic failures are caused by materials and manufacturing process defects. We have found that corrosion of electronic components is the cause of failure in about 20% of the items submitted to us for investigation.

Airframe corrosion prevention requirements are well specified by MIL-STD-1568, MIL-STD-1587, T.O. 1-1-2, and MIL-STD-889. It would be beneficial to the Air Force if corrosion prevention in electronic systems were ~~also~~ well documented. Existing documents, such as T.O. 1-1-689 and NAVAIR 16-1-540, are a step in the right direction. However, compulsory MIL specifications should be applied to Air Force electronic corrosion prevention. This is essential because corrosion in Air Force electronic systems contributes significantly to system failure.

Failure analysis investigations ~~with~~ which we have ~~been concerned include~~ aircraft circuit breakers, an antenna, printed wiring boards, a fuse, a linear steering position transducer, a stepper motor, an accelerometer, a disk recorder head, and electrical connectors ~~will be~~ presented. The cause of failure ~~will be~~ identified and possible means of preventing similar failures ~~will be~~ presented.

I. INTRODUCTION

The Electronic Failure Analysis Group of the Air Force Wright Aeronautical Laboratories' Materials Laboratory has investigated a large number of electronic and electrical failures. It has been established that about eighty-three percent of these failures are caused by materials and manufacturing process defects. Also, it has been verified that about twenty percent of the failures are caused by corrosion problems.

II. ANALYSIS TECHNIQUES

Moisture and contamination penetration into electronic systems has many detrimental effects, corrosion being one of these. In most electronic systems the geometries have been minimized for faster signal processing and higher density. This means that most metallizations are thin, or small in cross-sectional area, and that the individual metallizations are close together. In systems such as this, trace amounts of moisture and contamination may cause system failure. If the aluminum metallized surface of an integrated circuit is contaminated and if moisture is present, a slight amount of corrosion may result in an open integrated circuit conductor. This extreme sensitivity requires special caution when dealing with corrosion in electronic systems. Failure modes in electronic components and systems may be identified and related to field failures with environmental testing techniques. Figure 1 shows a typical twenty-four hour temperature and humidity cycle.

III. EXAMPLES OF ELECTRONIC AND ELECTRICAL CORROSION

The following are a few representative examples of corrosion induced failures.

A. Circuit Breakers

Numerous aircraft circuit breakers, Figure 2, have been identified as failed because their contact resistance when closed was considered too high. A number of circuit breakers from several different manufacturers were tested in the laboratory to determine the cause of the high resistance. The circuit break contacts were identified as either tungsten/silver or cadmium/-silver mixtures. Nine circuit breakers were exposed to a ten day humidity test (40°C and 95% RH). A destructive physical analysis of the parts found a small amount of corrosion on the tungsten/silver contacts. Because of this, a twenty day humidity test (49°C and 95% RH) was conducted on two contacts which had been cross-sectioned. After the twenty day test, the tungsten silver contacts were severely corroded while the cadmium/silver contacts exhibited very little corrosion, Figures 3 and 4.

A forty-eight hour salt fog test (35°C, 5% NaCl, pH 6.5 to 7.2, 1 to 2 cc/hr/80 cm^2 condensation rate) was conducted on seven of the circuit breakers. Two of the circuit breakers failed. This was caused by salt condensation on the contacts, Figure 5.

The results of our analysis indicate that the tungsten/silver contacts corrode much worse than the cadmium/silver contacts. Braze fluxes used to joint the contacts to the copper arm may contribute to corrosion. The contacts in all circuit breakers are improved by the mechanical wiping action of opening and closing the contacts several times. This should be done at periodic intervals. If the conduction of large currents is not required the cadmium/silver contacts show superior resistance to corrosion.

B. Antenna Marker Beacon

A corroded antenna marker beacon, Figure 6, was removed from an aircraft so that the source of corrosion could be determined. The beacon was x-rayed, Figure 7, and corrosion sites were visible in the radiograph. The antenna was opened and found to contain a polyamide foam, Figure 8. The antenna blade was removed from the foam, Figure 9, and found to be corroded too. Both the housing and blade were found to be aluminum. The housing was found to be plated with electroless nickel, Figure 10, and the blade was plated with a copper strike followed with a tin plate, Figure 11. It is believed that both the nickel plate and the copper/tin plate were porous. This permitted the penetration of moisture to the plating and aluminum interface. The presence of moisture and the anodic relationship of aluminum to nickel, or tin, resulted in a galvanic cell which caused pitting corrosion in the aluminum, Figures 12 and 13. These plating systems were used to maintain a high electrical surface conductance on the aluminum components. The corrosion has resulted in non-conductive surfaces which affect the electrical performance of the antenna. It was recommended that instead of plating the aluminum a chromate conversion coating be used.

C. Printed Wiring Boards

1. Flux Contamination

a. Dual In-line Packages

A printed wiring board was removed from an aircraft because of short circuits on the board, Figure 14. Blue-green corrosion products appeared around and under Dual In-line Packages (DIPs) on the board, Figure 15. A scanning electron microscope was used to analyze the corrosion products with characteristic x-ray analysis. Copper chloride was detected in the corrosion residue. Chlorides are a common contamination resulting from active solder fluxes and poor cleaning processes. It was recommended that a rosin type solder flux be used and that a board cleanliness test be performed after cleaning.

b. Conductor Traces

A ground base radar system was removed from nine months of storage to be tested. All electrical systems failed due to short circuits in many of the multilayer printed wiring boards. Upon examination the printed wiring boards appeared to have corroded conductor traces. Contamination and corrosion products had migrated to regions between conductor traces so that they were shorted out. See Figures 16 and 17. With characteristic x-ray analysis it was established that the contamination resulted from solder flux. A different cleaning procedure was recommended.

2. Flux on Board Components

Components from a printed wiring board have also been found to be contaminated with solder fluxes. Figure 18 shows a diode taken from a board. Figure 19, shows the corroded leads on this diode. Inadequate removal of flux residues causes many corrosion problems.

3. Water Soluble Flux

The use of a highly reactive solder flux may sometimes have unexpected consequences. Of course, the reactive flux makes the soldering procedure easier. Components or boards which have poor solderability may sometimes be used, or, some other device defects may be overcome but usually the reactive flux contaminates some parts of the electronic system so that it eventually causes more problems than it fixed.

A reactive water soluble flux was used on a number of printed wiring boards because some of the component leads exhibited poor solderability. The flux had a high chlorine content. During the soldering operation some of these chlorides were absorbed in the epoxy/-fiber glass board surface. After soldering, the boards are cleaned and conformally coated. This traps the flux near the surface of the board. The board cross-section is shown in Figure 20. The x-ray map for this area is shown in Figure 21. This chlorine may eventually affect the copper conductors in the board because the conformal coating will absorb moisture which could result in hydrochloric acid. Without the reactive water soluble flux this chloride surface contamination does not occur. If the components to be soldered are handled properly the soldering operation may be accomplished with less reactive fluxes. This is the best procedure.

D. Vacuum Tubes

Triode amplifier tubes were failing due to severe corrosion exterior and interior to the tubes, Figure 22. It was determined that the contaminant was a chloride and its source was most likely a highly corrosive chloride flux. Figure 23 shows localized corrosion on the outside of the tube and Figures 24 and 25 show the corrosion on the inside of the tube. Figure 26 shows a tube cross-section with the entrapped green corrodent clearly visible. It was recommended that all fluxes be thoroughly cleaned from the tube before sealing.

E. Fuse

After storage for several years some fuses were tested. The fuse failure rate was exceedingly high. The cause of this high failure rate required identification. Figure 27 shows the electronics when removed from the package. Note the white vibration dampening foam between the circular printed wiring boards. Upon analysis the foam was identified as polyvinyl

chloride. The circular boards were examined and it was found that they were heavily contaminated with chlorides. One of the boards was placed in a humidity cabinet for twenty-four hours with the results shown in Figures 28 and 29. Several failed plastic encapsulated transistors were opened, Figures 30 and 31. The arrow in Figure 30 marks the region in which the aluminum metallization was completely melted. The transistor surface was heavily contaminated with chlorides. It was found that these chloride contaminates were originating from the vibration dampening foam. The chloride penetrated the transistor by wicking up the metal leads extending through the plastic package. The polyvinyl chloride foam was replaced with a polyacrylic elastomer foam. The new foam material does not emit chloride contamination.

F. Steering Potentiometer

A linear feedback potentiometer is often used in the steering system for an aircraft nose wheel. A potentiometer of this type is shown in Figure 32. Several failures of this device have been observed. The cause of these failures was investigated. It was found that the ends of the potentiometer were exposed to the environment. Sufficient moisture and contamination were collected on the potentiometer in this area to cause corrosion. Figures 33 and 34 show corrosion products collecting on the glass header insulation around the incoming electrical wires. These corrosion products were shorting out the electrical leads on the potentiometer. The problem was corrected by providing this area of the potentiometer with sufficient protection to prevent the entrance of the moisture and the contamination.

G. Stepper Motor

Stepper motors are often submerged inside a fuel tank for cooling purposes. Of course, this means that the motor components, Figure 35, are then exposed to the fuel environment. In all cases, there is some small amount of water in the fuel. With sufficient time we have found that this water will hydrolyze polyimide wire insulation. These stepper motors had polyimide insulation on the field coils. After sufficient exposure to the water in the fuel some of the coils appeared as in Figure 36. This defect exposes the copper to the fuel. If some contamination in the fuel is available the copper ions will migrate into the fuel. This produces open circuits in the field coils as shown in Figure 37. This type failure may be avoided by hermetically sealing the field coils from the fuel, or by using a polysulfide insulation.

H. Accelerometer

An aircraft accelerometer was environmentally sealed instead of hermetically sealed. After extended use the accelerometer failed. Several accelerometers were tested in the Combined Environmental Reliability Test (CERT) chamber to establish the failure mode. The stresses used in the CERT chamber were selected to approximate the actual aircraft environment. The stresses included temperature cycling, humidity cycling, and altitude cycling, Figure 38. The accelerometer was electrically operational during a certain part of the cycle. After the accelerometer went through one hundred fifty cycles, it failed. The package was opened, Figures 39 and 40, and it was easily seen that corrosion residues were shorting out various parts of the circuits. This failure may be eliminated by hermetically sealing the accelerometer package.

I. Record Head

Disk recorder heads, Figure 41, were failing at a very high rate. This was happening in an area where the recorder operator was smoking cigarettes. Some of the particulate matter in the smoke was being trapped between the disk and the head. This contamination with the moisture available from the air was causing pitting corrosion in the head, Figure 42. It was recommended that the operator not smoke in the recording area and that the heads not be cleaned with a halogenated cleaning solvent. Use an alcohol.

J. Connector

1. Radar Modulator

The cause of failure of a radar modulator was identified as a corroded connector, Figure 43. Two connectors, one corroded and the other not, were joined by a wire insulated with a silicone rubber which had a chloride content less than 0.16%. The surfaces of both connectors were silver plated. The connectors were cross-sectioned, Figures 44 and 45, and the base material was identified as leaded brass. As shown in Figure 44, the silver plating on the uncorroded connector was $6.7\,\mu m$ thick. The silver plate on the corroded connector, Figure 45, was $5\,\mu m$ thick. Both plating thicknesses are too thin for adequate protection. The plating process should meet Federal Specification QQ-S-365C "General Requirements for Electrodeposited Silver Plating". This specification requires a nickel strike and a silver plating thickness of $13\,\mu m$. The corrosion was associated with a thin silver plating and it is believed a silver plating of specified thickness will eliminate the corrosion problem.

2. Low Voltage Connector

The corrosion of electrical connectors causes a large number of electrical failures. Figure 46 shows the corrosion on some aircraft connectors. These problems may be minimized when the connectors are installed in a horizontal position; when a loop is placed in the wire so water will not flow down the wire into the connector; when inhibitors are used on the connector pins and receptacle interior mating areas (MIL-C-81309, Type III); and when inhibitors are used on the external connector surfaces (AMLGUARD MIL-C-85054). It is

recommended that an aluminum connector with cadmium plate be used. The possibility of corrosion can be further minimized by using a chromate conversion coating over the cadmium plate.

K. Detector

A microwave detector failed due to corrosion, Figure 47. The ferrite core surface and cavity are shown in Figures 48 and 49. The detector case was constructed of nickel plated aluminum. The cavity lid has been removed and is shown in Figure 50. Note the corrosion along the edge. This corrosion is attributed to delamination of the nickel coating and the exposure of a dissimilar metal couple to high levels of moisture. The nickel coating delamination is the result of a poor plating process. This is usually caused by inadequate cleaning of the aluminum surface prior to plating. The pitting corrosion of the aluminum case and the poor lid-to-case seal allowed moisture to enter the internal case cavity, which resulted in the corrosion shown in Figures 48 and 49.

An alternate plating for the aluminum should be considered. Ion vapor deposited (IVD) aluminum should be used instead of nickel. A better lid-to-case seal should be obtained. This can be accomplished with appropriate gasket material.

L. Nickel/Boron Plated Panels

For many applications materials are required to meet conflicting requirements. An example of this is when metal panels are required to have corrosion resistance and good electromagnetic interference (EMI) protection. Such panels may be used to package electronic equipment.

Twelve nickel/boron coated aluminum plates, Figure 51, were given electrical and environment tests. Samples 1, 2, and 3 were 6062 aluminum and samples 4 and 5 were 2024 aluminum. The nickel/boron coating was 90% nickel with 10% boron diffused into it. A piece was cross-sectioned and it was found that the coating was made in two layers, Figure 52, each layer 0.625 mil thick. The faying surfaces were prepared for test by overlapping the pieces and drilling holes through the panels. The two plates were bolted together with nylon screws, Figure 53. A torque wrench was used to apply one inch pound of torque to each bolt.

The EMI protection requirement is that all faying surfaces maintain a resistance that does not exceed 2.5 milliohms after environmental exposure. A four point probe test fixture, Figure 54, was designed to measure the faying surface conductivity. The outer probes carried one ampere current and the inner probes were used to measure the voltage drop. For all measurements the current was reversed and the resistance values were averaged.

After the specimens were prepared as shown in Figure 53, five of them were submitted to humidity testing and one was kept as a reference. The humidity chamber was set at 95% relative humidity at 120°F for ten days. The specimens were removed after the first twenty-four hours and then every forty-eight hours for a visual inspection and, after re-torquing, a surface resistance measurement. The surface resistance measurements for the specimens are shown in Table I. The condition of sample 1 after the ten day humidity exposure is shown in Figure 55. This sample is typical.

The five samples were disassembled and cleaned with distilled water in preparation for a salt fog test. The chamber was set-up in accordance with ASTM Standard B-117. A five percent salt solution of 95°F and condensation rate of 1-2 mils/hr/80 cm inside the chamber were used to create the salt fog atmosphere. The specimen plates were bolted together again, as during the humidity test, and exposed to the salt fog for 336 hours, or 14 days. The samples were removed periodically for visual inspection and electrical testing. The samples were washed with distilled water, dried for two hours, and re-torqued before being electrically tested. After testing, the samples were then returned to the chamber until 336 hours of testing were completed. The results of the electrical testing are shown in Table II. All five samples exhibited signs of corrosion after 144 hours. The number 4 and 5 samples exhibited severe corrosion, Figure 56. The surface resistances of these samples were higher than the other samples, but still below the maximum of 2.5 milliohms. After 336 hours in the salt fog, samples 4 and 5 again exhibited severe corrosion, Figure 57. Only the surface resistance of sample 4 was above 2.5 milliohms. After electrical testing, the samples were disassembled. The overlapping surfaces of all samples exhibited corrosion, Figure 58. Pictures of the samples with the least and most corrosion are shown in Figures 59 and 60.

The nickel/boron coated aluminum plates passed the humidity testing but they did not do as well in the salt fog testing. The corrosion was most severe when a break occurred in the nickel/boron coating and allowed the salt solution to penetrate into the coating/aluminum interface. The anodic relationship of aluminum to nickel resulted in pitting corrosion of the aluminum and the formation of aluminum oxide. The aluminum oxide is an excellent insulator and will significantly increase the surface resistance of the panel. The plating should be free of surface imperfections and protected from scratches which could break the coating and result in corrosion.

IV. CONCLUSIONS

The examples of corrosion in electronic equipment listed above were obtained from actual case histories, in an Electronic Failure Analysis Laboratory. Of all the projects submitted to this laboratory, 83% of the failures are caused by materials and manufacturing process defects. It was established that corrosion was the cause of about 20% of the failures.

The recommended fixes always interrupt the electrochemical circuit required for corrosion; anode, cathode and electrolyte (so that electrical conduction may take place between the anode and cathode). The fixes either remove the electrolyte, or insulate the anode, or remove the cathode. Once these fixes are accomplished, there is usually a very large cost savings for the customer and a significant improvement in the electronic equipment reliability.

TABLE I. Faying Surface Resistance of Plates Exposed to High Humidity

Sample Number	Average Surface Resistance (microhms) @ 1 ampere					
	Initial	After 24 hrs	After 48 hrs	After 96 hrs	After 192 hrs	Final 240 hrs
1	140	245	256	201	226	183
2	130	282	263	220	208	214
3	134	207	230	219	230	243
4	146	322	205	202	198	202
5	144	374	333	346	356	326

TABLE II. Faying Surface Resistance of Plates Exposed to Salt Fog

Sample Number	Average Surface Resistance (microhms) @ 1 ampere					
	Initial	After 24 hrs	After 48 hrs	After 96 hrs	After 192 hrs	Final 240 hrs
1	198	155	143	203	274	277
2	212	136	134	211	255	260
3	273	162	152	158	155	161
4	220	176	200	799	15369*	20727
5	198	285	298	332	400	632

* Exceeded 2.5 milliohms

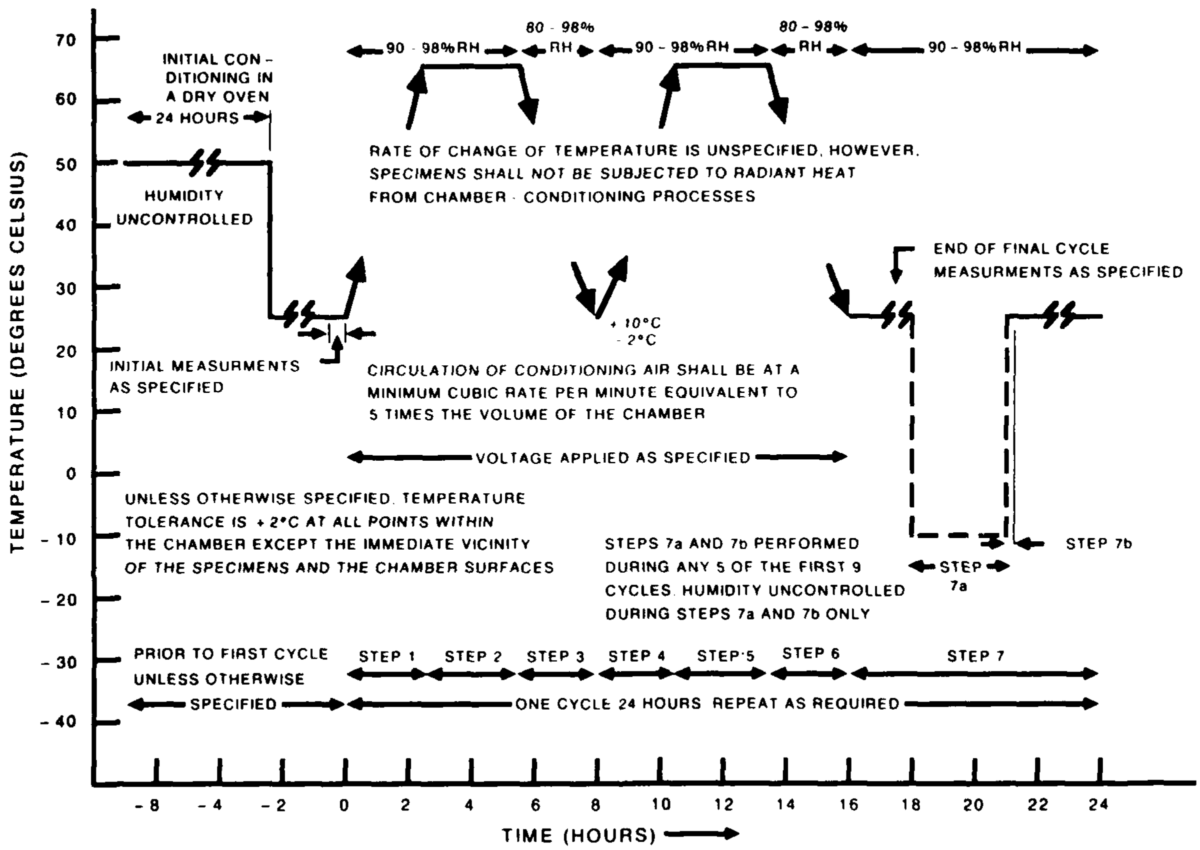

Figure 1. Graphical representation of thermal and humidity cycling.

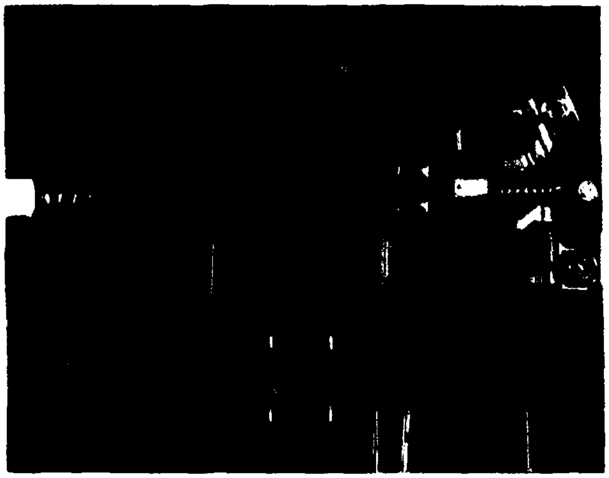

Figure 2. Exploded view of aircraft circuit breaker.

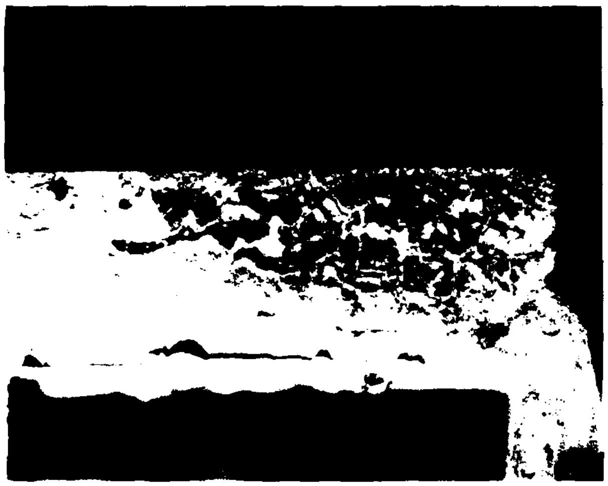

Figure 3. Cross-sectional view of tungsten/silver contact after twenty day humidity test.

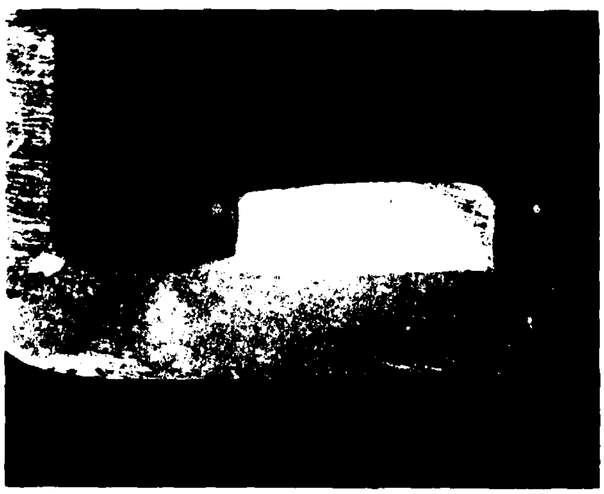

Figure 4. Cross-sectional view of cadmium/silver contact after twenty day humidity test.

Figure 5. Failed contact after forty-eight hour salt fog test.

Figure 6. Failed antenna marker beacon caused by corrosion.

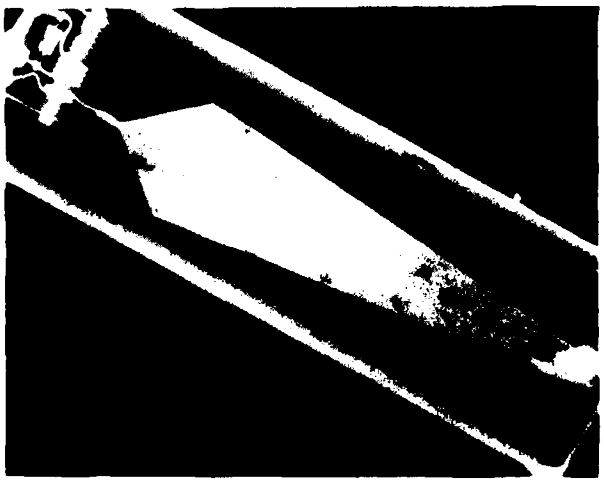

Figure 7. X-ray radiograph shows areas of corrosion.

Figure 8. Polyamide foam inside beacon.

Figure 9. Antenna blade removed from housing.

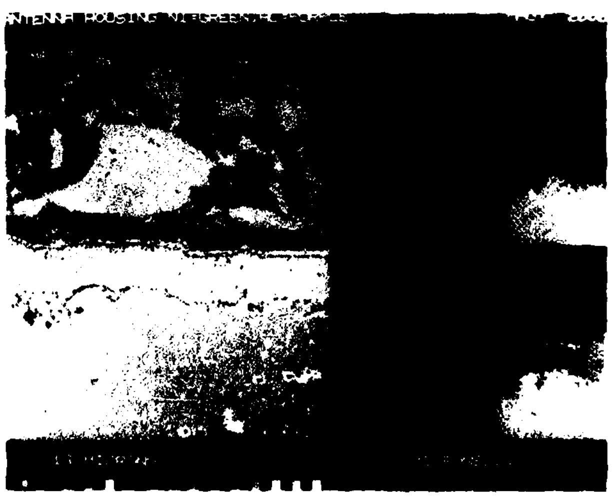

Figure 10. X-ray map of cross-sectional area of nickel plate on aluminum housing of beacon. See Figure 12.

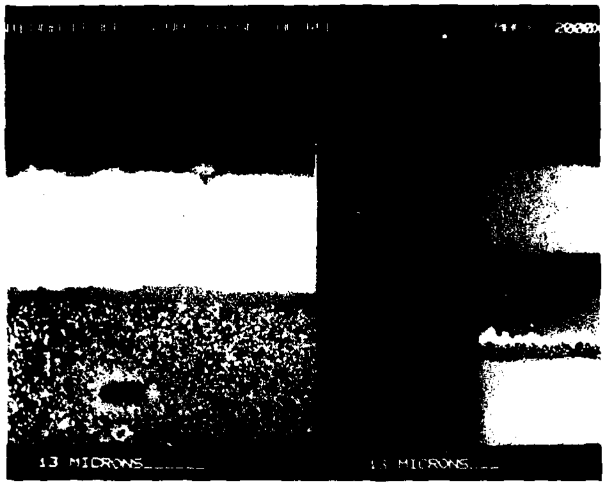

Figure 11. X-ray map of cross-sectional area of copper/tin plate on aluminum blade of beacon. See Figure 13.

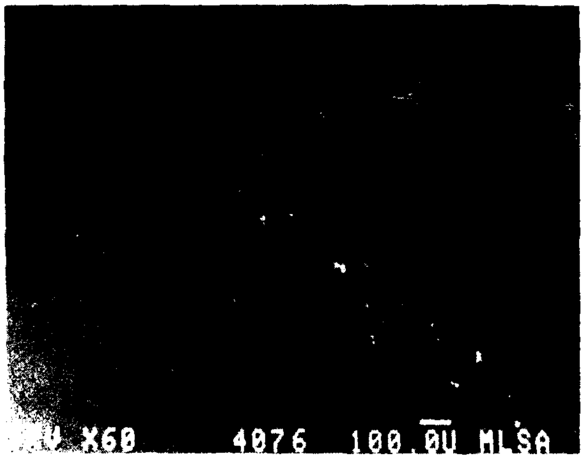

Figure 12. Cross-sectional SEM micrograph of nickel plating on aluminum housing of beacon. Note areas of lifted nickel plating.

Figure 13. Cross-sectional SEM micrograph of copper/tin plate on aluminum blade of beacon. Note areas of lifted plating.

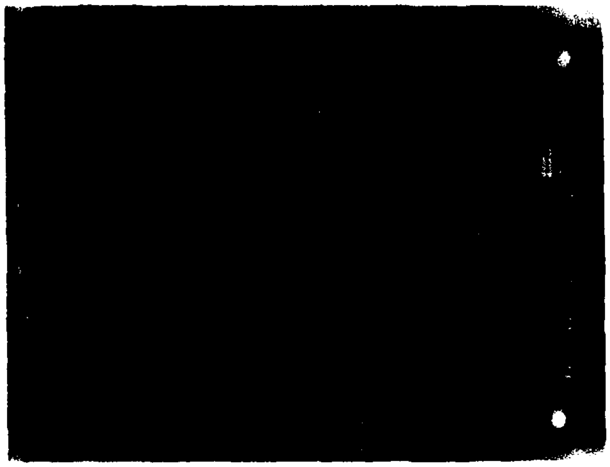

Figure 14. Component side of failed PWB. Note flux contamination on board.

Figure 15. One of the DIPs shown in Figure 14 at higher magnification. Leads are shorted out by flux contamination.

Figure 16. Component side of failed PWB.

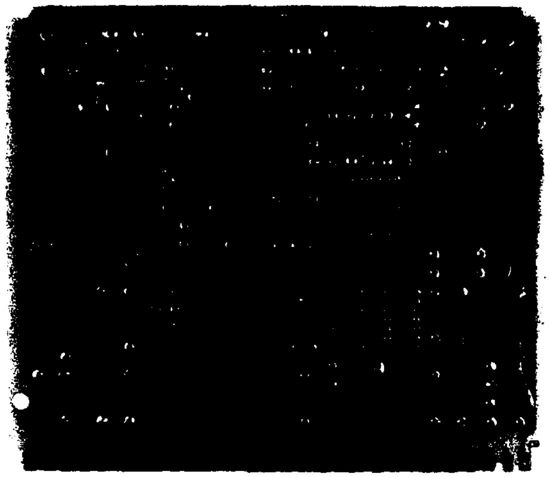

Figure 17. Backside of board shown in Figure 16. Note corrosion on conductors and white areas of mealing on board.

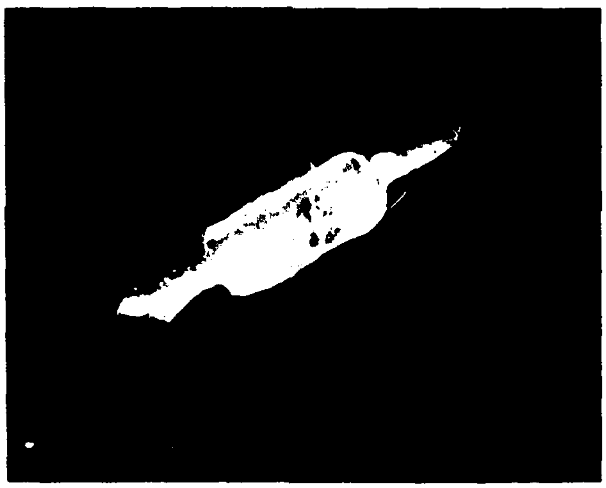

Figure 18. Diode removed from failed PWB.

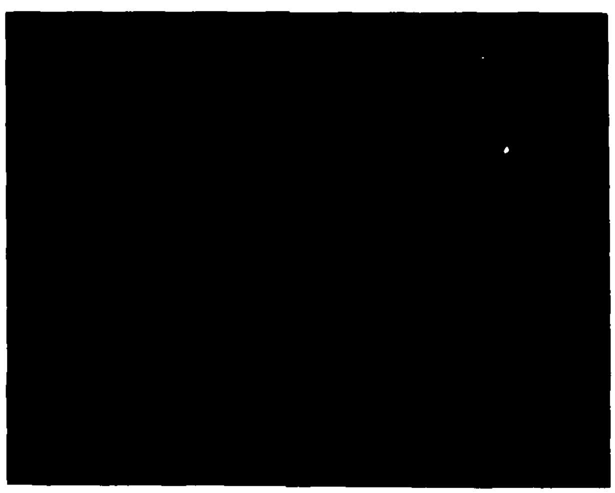

Figure 19. Lead on diode shown in Figure 18. Note corrosion on lead.

Figure 20. SEM micrograph of cross-sectional area of PWB. Constitute parts from the left are: void, conformal coating, solder, copper, and epoxy/fiberglass board matrix. See Figure 21.

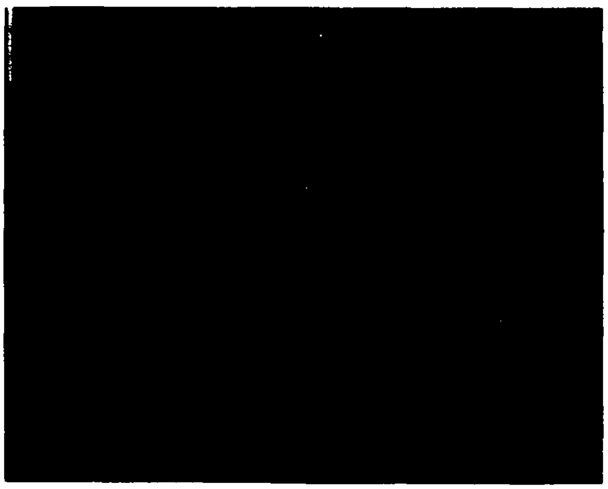

Figure 21. X-ray map of area shown in Figure 20. Gray area is copper. Blue region on copper is solder. Green lower central region is chlorine in surface of epoxy/fiberglass board matrix. See Figure 20.

Figure 22. Failed triode amplifier tubes with corrosion interior and exterior to the tubes.

Figure 23. Exterior corrosion on the triode.

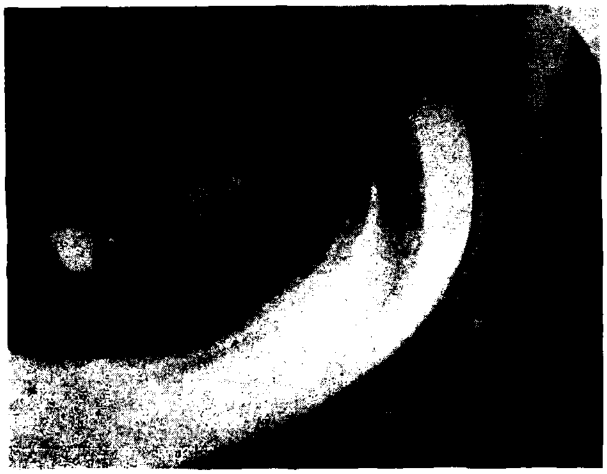

Figure 24. Interior corrosion in the triode. Glass envelope has not been removed.

Figure 25. Interior corrosion in the triode. Glass envelope has been removed.

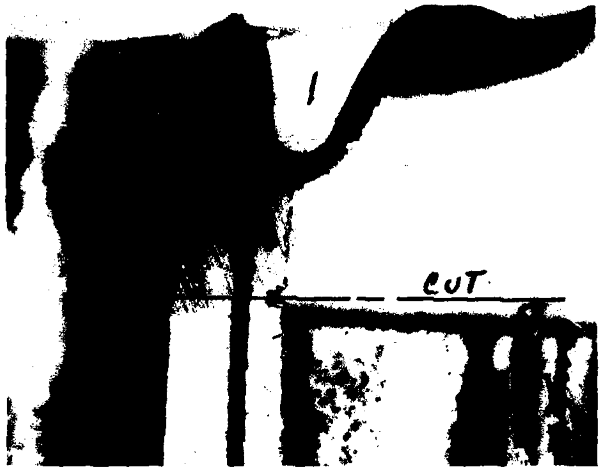

Figure 26. Cross-section of triode shows entrapped corrodent.

Figure 27. Electronic device with white vibration dampening foam between PWBs.

Figure 28. Corrosion on board resulted from chloride contamination. See Figure 29.

Figure 29. Enlargement of area shown in Figure 28.

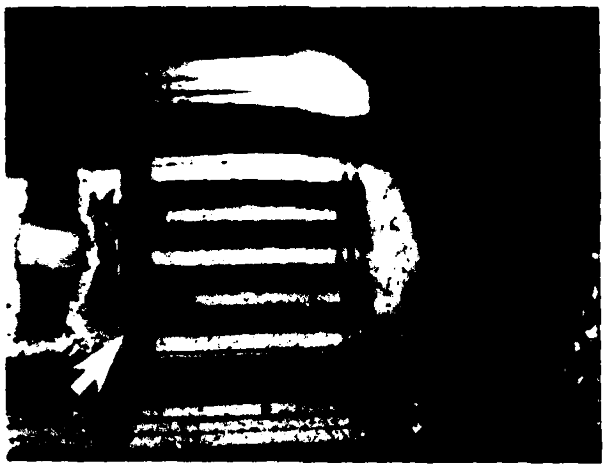

Figure 30. Failed transistor with high surface chloride contamination. See Figure 31. Arrow marks site of open aluminum conductors.

Figure 31. SEM micrograph enlargement of region marked by arrow in Figure 30.

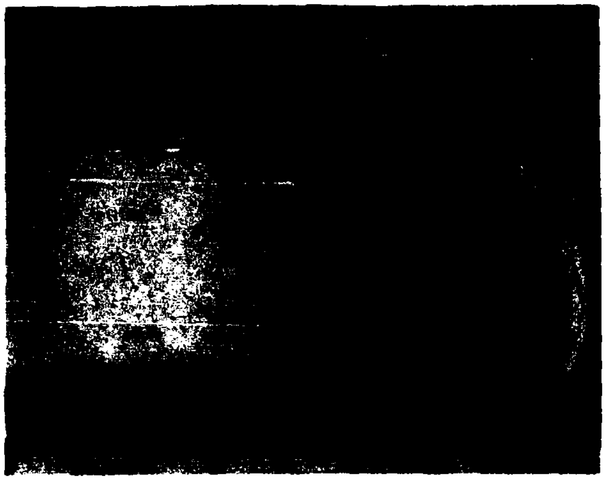

Figure 32. Linear feedback potentiometer.

Figure 33. Arrow marks corrosion residue on potentiometer exterior which shorts out electrical leads.

Figure 34. Enlargement of site marked by arrow in Figure 33.

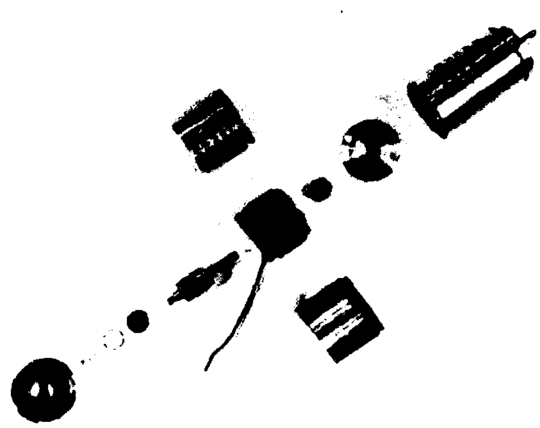

Figure 35. Exploded view of stepper motor.

Figure 36. Cracked polyimide insulation on field coils.

Figure 37. Arrow marks site of open field coils.

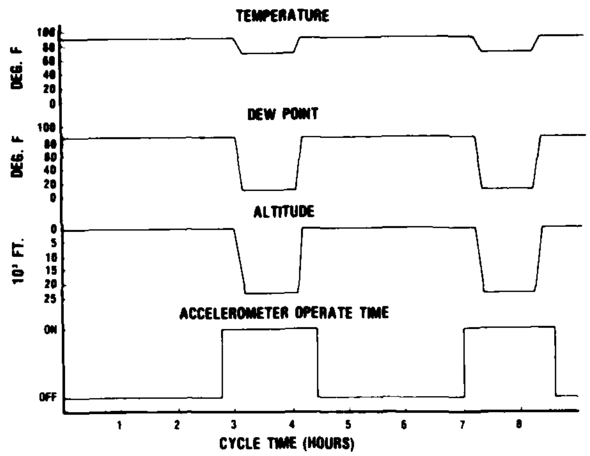

Figure 38. Spectrum of CERT stresses applied to accelerometer.

Figure 39. Failed accelerometer opened for inspection. Arrows mark regions of corrosion.

Figure 40. Enlargement of area shown in Figure 39.

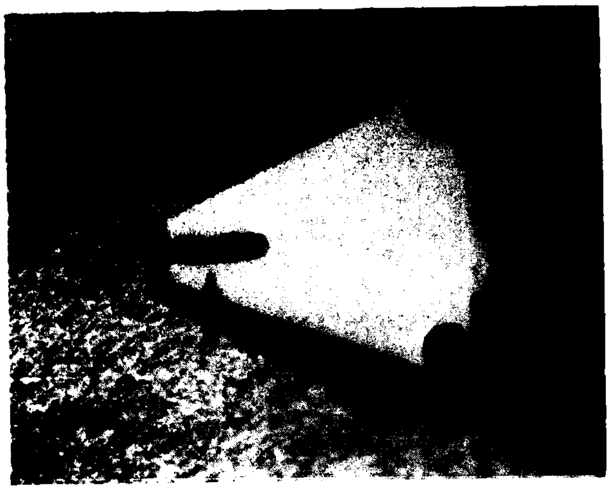

Figure 41. Disk recorder head. Arrow marks metallic head.

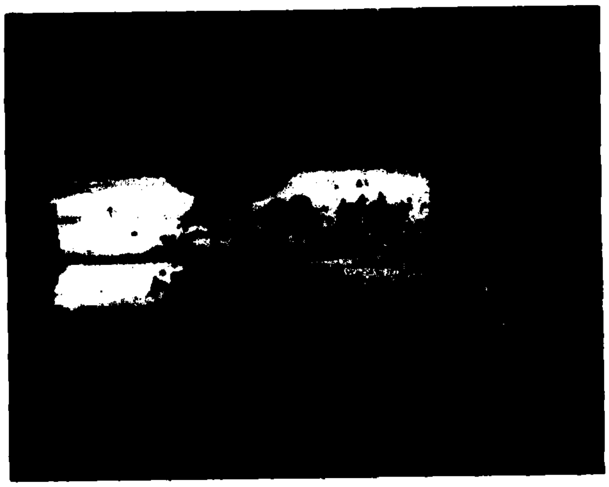

Figure 42. Enlargement of head marked by arrow in Figure 41.

Figure 43. Corroded connector on radar modulator.

Figure 44. Cross-sectional area of good connector.

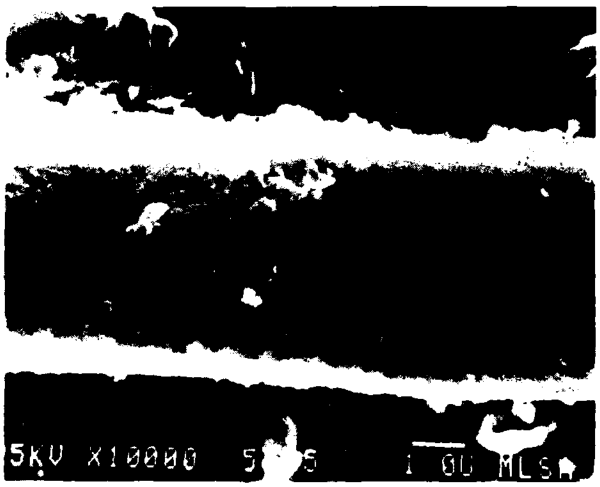

Figure 45. Cross-sectional area of failed connector.

Figure 46. Corroded electrical connector on avionic equipment.

Figure 47. Corroded microwave detector.

Figure 48. Ferrite core in detector.

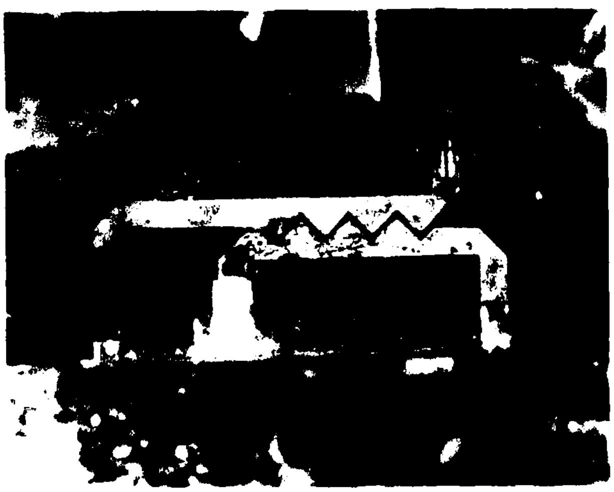

Figure 49. Detector cavity.

Figure 50. Corrosion on the nickel plated aluminum lid.

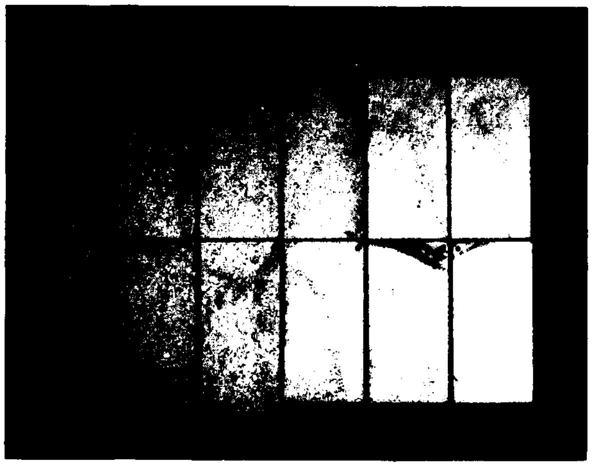

Figure 51. Twelve nickel/boron plated aluminum panels to be tested.

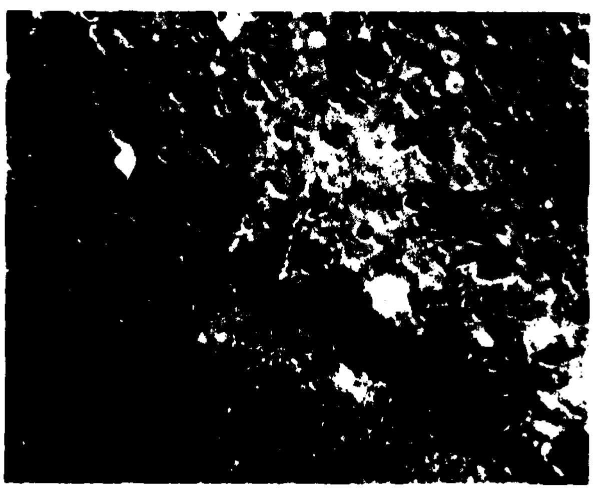

Figure 52. Cross-sectional view of nickel/boron plating on the aluminum panel.

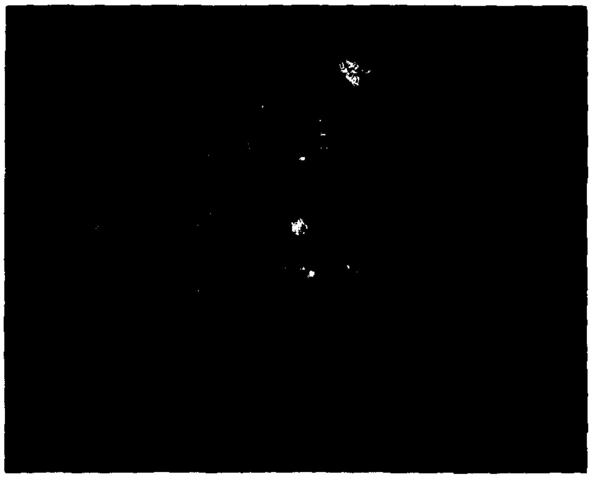

Figure 53. Two panels bolted together with nylon bolts.

Figure 54. Test fixture used to measure electrical resistance between two panels.

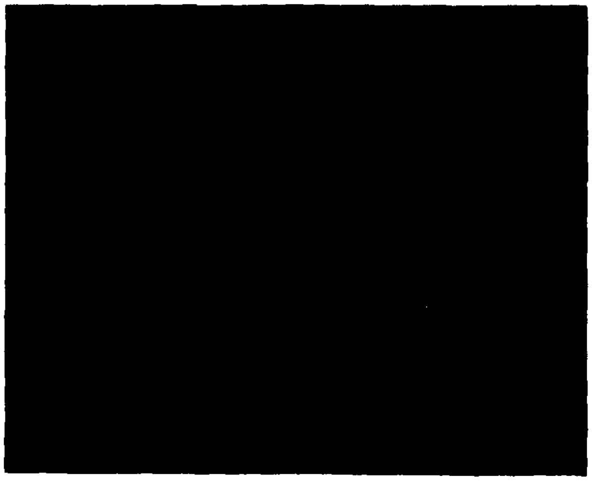

Figure 55. Sample 1 after humidity testing.

Figure 56. Sample 4 after 144 hours of salt fog testing.

Figure 57. Sample 4 after 336 hours of salt fog testing.

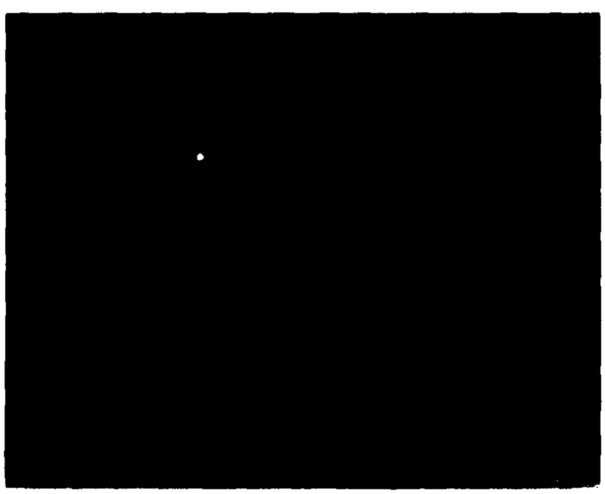

Figure 58. Surfaces of all samples after 336 hours of salt fog testing.

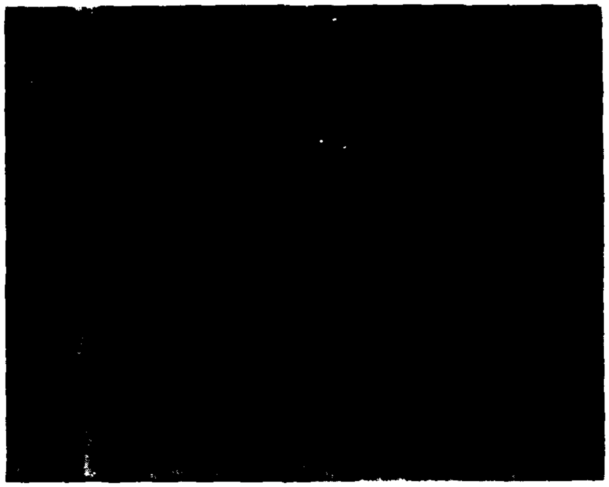

Figure 59. Sample surface with least corrosion after 336 hour salt fog test.

Figure 60. Sample surface with most corrosion after 336 hour salt fog test.